

THE RHEOLOGY OF ICE AT LOW STRESSES; APPLICATION TO THE BEHAVIOR OF ICE IN THE EUROPEAN SHELL. P. Duval¹ and M. Montagnat², ¹Laboratoire de Glaciologie et Géophysique de l'Environnement/CNRS, B.P. 96, 38402 St. Martin d'Hères cedex, France, duval@lgge.obs.ujf-grenoble.fr, ²LTPCM/INPG, B.P. 75, 38402 St. Martin d'Hères cedex, France, maurine.montagnat@ltpcm.inpg.fr

Introduction: The existence of an ocean in Europa is attributed to tidal heating [1], [2]. The thickness of the ice shell is poorly constrained. Surface features are in agreement with the occurrence of thermally induced solid-state convection within the lowest part of the ice shell [3]. The ice shell would be therefore composed of a thick brittle conductive layer overlying a convective sublayer [4], [5]. Tidal heating would be located in the bottom of the convective layer. These results are obviously largely dependent on the viscosity of the ice. Tidal stresses are estimated of the order of 0.04 MPa with a strain rate of about 10^{-10} s^{-1} whereas convective stresses would be substantially lower. These mechanical conditions are found in polar ice sheets for which the lower bound for strain rates is about 10^{-13} s^{-1} near the surface of the East Antarctic ice sheet.

The rheological behavior of ice at low stresses is subjected to extensive studies to improve ice sheet flow models. In situ and laboratory measurements are needed for a better knowledge of the ice flow law at these low strain rates and for the construction of polycrystals models used to simulate the mechanical behavior of isotropic and anisotropic ices. A review of recent results on the behavior of pure ice is given here with emphasis placed on the physical deformation mechanisms which control the deformation of ice at low stresses. Particular attention is paid to the variation of the viscosity with stress, temperature and grain size in the deformation conditions of the European ice shell.

The ice flow law: From several laboratory studies, the flow law for deviatoric stresses lower than 0.1 MPa, is associated with a stress exponent lower than 2 [6, 7, 8]. Results can be questioned because of the long time needed to obtain reliable data. But, a clear indication of the decrease of the stress exponent below 0.1 MPa is found from the analysis of field data. A stress exponent of about 2 is found from boreholes deformation measurements in Greenland [9]. Convincing results on the flow law at low stresses were obtained from bubbly ice density and bubbles pressure measurements [10]. Data support a flow law with a stress exponent lower than 2 at low stresses.

The deformation modes: Indication of deformation mechanisms is obtained by comparing the deformation of ice single crystals well oriented for basal slip and the deformation of isotropic polycrystals [8]. The relatively low strain rates of polycrystals cannot be explained by a geometric effect related to the random orientation of crystals. Basal slip is put forward as the main deformation mode [11]. Basal slip providing two slip systems, two other slip systems should be activated to respect the stress compatibility and the continuity of the deformation across grain boundaries [12]. Slip on prismatic and pyramidal planes are generally suggested as additional slip systems. But, the activity of these slip systems given by several polycrystals models keeps a value lower than 10% for isotropic ice [11] and the occurrence of such slip is not proved. Dislocation climb can be assumed as a complementary deformation mode [13]; but, the dissociation of dislocations in the basal plane and the relatively low diffusion rate of oxygen atoms make uncertain this assumption. Grain boundary sliding (GBS) can be also suggested. But, there is no evidence of the occurrence of such process in the flow conditions of ice sheets. This mechanism was put forward as the predominant deformation mode of polar ice by Goldsby and Kohlstedt [14]. This assertion was reached from laboratory experiments carried out on very fine grained-ices. Extrapolation to conditions found in ice sheets was questioned by Duval and Montagnat [15]. The microstructure and the development of the preferential orientation of ice crystals is clearly no in accordance with GBS as the dominant deformation mode in polar ice sheets. GBS could be invoked to accommodate basal slip; this deformation mode has nothing doing with the behavior of superplastic materials. With regard to the accommodation of basal slip, it is significant to discuss all physical processes which occur in ice sheets. Grain boundary migration (GBM) associated with the normal grain growth and continuous recrystallization appears to be an efficient recovery process [16], [17]. By sweeping dislocations located in the front of moving grain boundaries, GBM prevents kinematics hardening caused by the incompatibility of the deformation

between grains. It is not a deformation mode, but it contributes to keep high the activity of basal slip systems. The analysis of the microstructure of single crystals from deep ice cores by X-ray diffraction has revealed a significant distortion of the lattice accommodated by geometrically necessary dislocations [18]. These strain heterogeneities are related to the strong anisotropy of the ice crystal inducing a significant mismatch of slip at grain boundaries. The role of strain gradients in the plastic behavior of ice polycrystals appears to be significant. In conclusion, by accommodating basal slip, several physical processes, identified in ice sheets, must contribute to the large activity of the basal slip systems. The preponderance of intracrystalline slip is moreover in agreement with the simulation of the development of fabrics by micro/macro approaches [11].

Application to the European ice shell: Deformation conditions in the assumed convective layer of Europa are very similar to those described above for polar ice sheets. By assuming pure water ice, the deformation mechanism with a stress exponent slightly lower than 2 is likely. But, considering that convective stresses are significantly less than the fluctuating tidal stresses, a newtonian viscosity should be assumed for this process [4]. An important point is the effect of grain size and water content since temperate ice could be present in the convective layer. There is a clear indication from in situ measurements that strain rate is depending on grain size in polar ice sheets [19], [20]. The exact relationship between strain rate and grain size is not well defined. But, it seems clear that strain rate is increasing with decreasing grain size. This result is not in contradiction with physical processes put forward to accommodate basal slip in ice sheets. The efficiency of GBM to reduce the internal stress field induced by the incompatibility of deformation between grains is depending on grain size

[18]. Grain boundary sliding and strain gradients seen as accommodation processes are also depending on grain size. Concerning the effect of temperature near melting point, extensive studies were developed by the glaciological community [21], [22]. The viscosity of ice containing some percents of water can be ten times lower than that containing a negligible melt phase [21]. It is significant to point out that the viscosity of ice containing 7% of melt is of the order of 10^{13} Pa.s [22]. The first role of the liquid phase would consist of attenuation of the internal stress field which develops during the primary creep [22].

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